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THESIS

Localization of Acoustic Transients in Shallow Water Environments

by

Charles Louis Nicholson

December 1992

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Ching-Sang Chiu

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**Localization of Acoustic Transients
in Shallow Water Environments**

by

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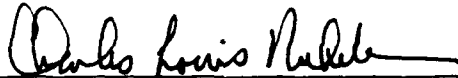
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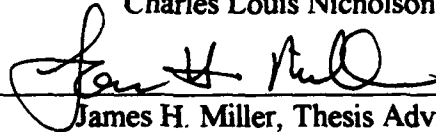
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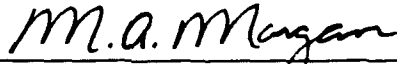
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ABSTRACT

Determination of an underwater target's position using passive acoustic sensors is of considerable use for the Navy, both for anti-submarine warfare (ASW) and underwater surveillance. This thesis proposes and develops localization algorithms capable of passively determining the location of a transient source given some broad constraints. In particular, this thesis investigates the effect of the source signal uncertainty on localizer performance. The localization process consists of two parts. First, a time domain propagation modeling code determines the impulse response of the environment from all possible source locations to a single hydrophone. This program predicts the signal as it would appear at the receiver from a grid of possible source locations. Second, source localization results from finding the maximum correlation between the positionally dependent, numerically modeled signals and the actual received signal. The position of the maximum cross correlation reveals an estimate of source position. Using model to model correlation, this technique successfully localized acoustic sources in both Monterey Bay and Barents Sea scenarios.

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I. INTRODUCTION

The localization of transient acoustic signals is of potential use to the United States Navy both for antisubmarine warfare and underwater surveillance. The ability to localize a signal with only the received signal data and with little or no *a priori* information about the original source would be a significant advance in both these areas.

The classification of these signals is of similarly high interest. It would appear that all signals of a short duration nature could have a myriad of frequency characteristics. To conduct a true matched signal cross-correlation, knowledge of these signal parameters would help immensely. Computer simulated localization experiments have shown that near perfect correlation was possible using the signal transmitted through the model from the source then correlated with a like signal sent back through the model from the receiver to the source location. As part of the development of this technique, this "matched-signal" algorithm was tested for several varied cases to confirm reliability.

In the history of broadband source localization, most previous work involves methods that operate in the time domain. The earliest matched-signal work, which ironically came as a precursor to the recent research in matched-field theory, was conducted by Parvulescu¹ and Parvulescu and Clay,² in which an impulse was transmitted by a source in a given environment, the resulting time series was recorded at a receiver and the time-reversed time series was re-transmitted through the source. Both laboratory and ocean experiments indicated that the received signal reached a peak when the source and the receiver were at the original positions, rather than any other positions. The state of computer technology in the period of these experiments limited the tests to primarily empirical analog efforts with no practical tactical applications.

More recently, Clay has re-examined the matched-signal concept as a time-domain matched-field method. In this algorithm, a computer propagation model predicts the impulse response for a number of source positions, counter to physically measuring the impulse response of the laboratory or ocean environment. The time-domain signal matching method then localizes the source.^{3,4} Clay also extended the method to multiple receivers by cross-correlating the matched-field outputs for pairs of receivers. The research continued with Li and Clay applying the methods to experimental data measured in rigid-walled wedges and flat waveguides.^{5,6} Hodgkiss and Brienzo successfully applied the method to short-range localization of impulsive signals in deep water.⁷ Later, Frazer and Pecholcs proposed generalizations to the matched-signal algorithm for a single hydrophone by considering different norms.⁸ Most recently, Westwood developed a broadband matched field algorithm that operates in the frequency domain without *a priori* source knowledge.⁹

A localizer based on the correlation of a signal with that of a signal sent through a propagation model, i. e., matched-signal, requires a prototype for a signal. Given that the transmitted transient is assumed to be an impulse in time, a impulse response function model of the signal through the medium would possibly suffice. As did Westwood,⁹ this thesis will show that, indeed, under given constraints of both the environment and the signal to be localized, that this algorithm will work.

II. MODELING THE OCEAN TRANSFER FUNCTION

A. PARABOLIC EQUATION MODEL

Under the assumptions of linearity and time invariance,* an acoustic signal at a receiver can be found from the convolution of the source pressure signal with the ocean impulse response,¹⁰

$$p(r_r, z_r, t) = \int_{-\infty}^{\infty} p(r_s, z_s, t - \tau) h(r_s, z_s, r_r, z_r, \tau) d\tau, \quad (1)$$

where p is pressure, r_r is the receiver range, z_r is the receiver depth, r_s is the source range, z_s is the source depth, and t is time. The Fourier transform of the equation gives the resulting pressure at the receiver in the frequency domain

$$P(r_r, z_r, f) = P(r_s, z_s, f) H(r_s, z_s, r_r, z_r, f) \quad (2)$$

where P and H are Fourier transforms of the functions in (1) such that

$$p(r_r, z_r, t) = \int_{-\infty}^{\infty} P(r_r, z_r, f) e^{-j2\pi ft} df \quad (3)$$

and

* The assumption of time invariance would at first seem to be unrealistic for the ocean. However, the ocean need only be quasi-time-invariant, i.e. the properties of the medium do not change over the time it takes to propagate from source to receiver. This is often referred to as the "frozen approximation".

$$h(r_r, z_r, r_s, z_s, t) = \int_{-\infty}^{\infty} H(r_r, z_r, r_s, z_s, f) e^{-j2\pi ft} df \quad (4)$$

The formulation of the ocean transfer function becomes critical and the best approach to this end remains in the solution of the Helmholtz equation.

The Helmholtz equation governs the sound pressure field excited by a point harmonic source, therefore the Helmholtz equation evaluated at different frequencies will determine the transfer function. Assuming the complex pressure $p(t, \mathbf{r})$ satisfies the pressure release boundary condition $p(t, \mathbf{r}) = 0$ at the surface and the outgoing radiation condition at infinity, the reduced wave equation in the water column becomes

$$\nabla^2 p(t, \mathbf{r}) + K^2 p(t, \mathbf{r}) = -4\pi\delta(z - z_0) \quad (5)$$

where $p(t, \mathbf{r})$ is the acoustic pressure (Pascals) and K is the complex wave number.¹⁰ Assuming that the acoustic pressure has a time harmonic dependence, then substituting this acoustic pressure into the wave equation results in the time independent Helmholtz equation. The solution to this equation can be obtained by the parabolic equation method to approximate the solution.

Historically, the parabolic equation method has been limited to modeling narrow angle sound energy propagation. More recently, parabolic equation acoustic algorithms have modeled sound propagation with propagation angles of up to 90 degrees from the horizontal.^{11,12} Additionally, the technique readily implements models for coarse, rugged bathymetry and/or variable density stratification. In this thesis, the Collins' parabolic equation approximation method¹³ computes the ocean transfer function.

The Helmholtz equation can be solved in cylindrical coordinates by removing the cylindrical separation effect terms and assuming negligible azimuthal variations. By defining $Q = \sqrt{r}P$ and substituting into Eq. 5, the Helmholtz equation can be factored in out-going and incoming solutions. The out-going equation is

$$\frac{\partial Q}{\partial r} = jk_0 \sqrt{1 + X} Q \quad (6)$$

where

$$X = k_0^{-2} \left(k^2 - k_0^2 + \frac{\partial^2}{\partial z^2} - \frac{1}{\rho} \frac{\partial \rho}{\partial z} \frac{\partial}{\partial z} \right). \quad (7)$$

This algebraically-difficult square root operator can be approximated by a series expansion.

The Finite Element Parabolic Equation (FEPE)¹¹ of Collins uses a family of Padé series¹⁴ to create higher order parabolic equations which are accurate for propagation angles close to the vertical. With Padé series expansion the square root operator becomes

$$\sqrt{1 + X} - 1 = \sum_{i=1}^n \frac{a_{i,n} X}{1 + b_{i,n} X} \quad (8)$$

where

$$a_{i,n} = \frac{2}{2n+1} \sin^2 \frac{i\pi}{2n+1} ; b_{i,n} = \cos^2 \frac{i\pi}{2n+1}$$

where n is the number of Padé terms. The number of Padé terms used determines the angle of sound propagation which can be accurately modeled, with excellent results up to 90 degrees for $n=4$.¹²

To derive the parabolic form of the complex pressure, Q is expressed as

$$Q = \sqrt{r} P = U e^{jk_0 r} \quad (9)$$

By solving for P and equating this to the ocean transfer function, Eq. 9 becomes

$$H = P = \frac{1}{\sqrt{r}} U e^{jk_0 r} \quad (10)$$

Now substituting into Eq. 2, the frequency domain pressure signal becomes

$$P(r_r, z_r, f) = P(r_s, z_s, f) \frac{1}{\sqrt{r}} U(r_s, z_s, r_r, z_r, f) e^{jk_0 r} . \quad (11)$$

Taking the Fourier transform, combining exponential terms and defining $t' = t - r/c_0$, the resulting received pressure signal becomes

$$P(r_r, z_r, t') = \frac{1}{\sqrt{r}} \int_{-\infty}^{\infty} P(r_s, z_s, f) U(r_s, z_s, r_r, z_r, f) e^{-j2\pi f t'} df \quad (12)$$

which can be solved efficiently with the inverse fast Fourier transform (IFFT).

To solve the Helmholtz equation using the Collins FEPE, several assumptions are made. Specifically, the acoustic pressure has time-harmonic dependence as mentioned above. In addition, the sound source is an omnidirectional point source and backscatter is neglected.

B. THE OCEAN GRID

The localization algorithm requires two assumptions with regard to the *a priori* knowledge of the source. One, the source must have been propagated from a location in the ocean waveguide along a specifically known azimuth. The second assumption requires that the source emanate from a location on the superimposed grid. Figure 1 depicts representative grid. Considering that most common receiver is an array of hydrophones, the first assumption takes advantage of beamforming to localize in azimuth. Later discussion will expand on the second assumption requirement. These two assumptions lead to the creation of a 'grid' of possible source locations with axes of depth (z) and range (r) along the azimuth given.

C. RECIPROCITY

The final aspect to consider is that of reciprocity. With each grid point there is an associated transfer function from that point to the receiver. If it can be claimed that a signal sent from point **a** to point **b** in the ocean will appear at **b** the same as a signal sent from point **b** to **a** would appear at **a**, then reciprocity is considered to exist¹⁵. Symbolically, this is

$$\bar{h}(r_s, z_s, r_r, z_r, t) = \bar{h}(r_r, z_r, r_s, z_s, t) \quad (13)$$

or

$$\bar{H}(r_s, z_s, r_r, z_r, f) = \bar{H}(r_r, z_r, r_s, z_s, f) \quad (14)$$

where the \bar{H} indicates the transfer function in the forward direction and the \bar{H} indicates the transfer function in the reverse direction. This assumption is fairly accurate since the ocean and surrounding environment is for the most part reversible, except in the presence of strong currents.

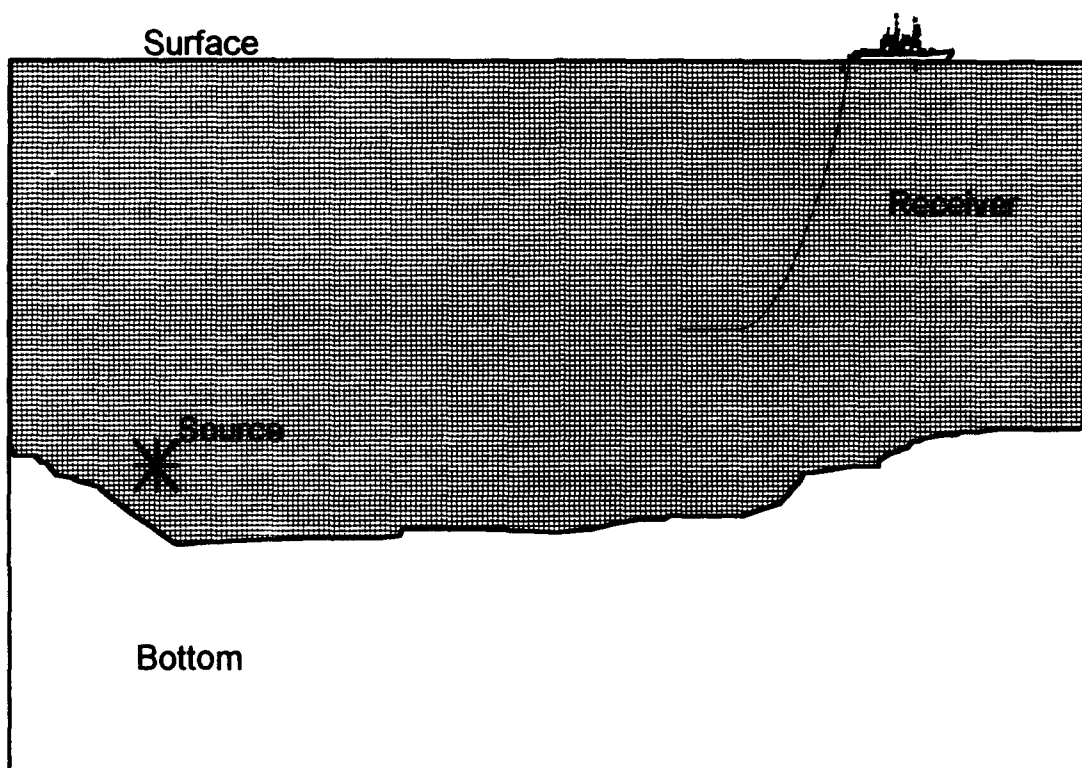


Figure 1: Example of grid and source-receiver relationship

III. LOCALIZATION METHODOLOGY

The localizer works by using reciprocity and transmitting the original source signal back from the receiver to all the points in the grid. The resulting 'reverse' transmissions are then correlated with the original received signal, i.e., $\tilde{H}(\mathbf{r}, z)S$ is correlated with $D \equiv \tilde{H}S$ for all (\mathbf{r}, z) in the grid, such that

$$R_{om}(\mathbf{r}, z; \tau) = \frac{\text{ifft}(D \cdot (\tilde{H})^*(\mathbf{r}, z))}{\sigma_D \sigma_{\tilde{H}}} . \quad (15)$$

The location with the maximum cross correlation will be the original source location. This method is dependent on knowing the original source signal characteristics.

A variation in the algorithm results when lacking characteristics of the original signal. In this case, broadband signals can be localized by assuming that the transient signal will only result in a scaling of the transfer function in the frequency domain. The signal being an impulse in the time domain will be a constant in the frequency domain. Therefore, the transfer function \tilde{H} at all points in the grid are correlated with the received signal $D \equiv \tilde{H}S$,

$$R_{om}(\mathbf{r}, z; \tau) = \frac{\text{ifft}(D \cdot \tilde{H}^*(\mathbf{r}, z))}{\sigma_D \sigma_{\tilde{H}}} . \quad (16)$$

This will not result in a perfect correlation, but the maximum value of the correlation function at each point in the grid should reveal the source. Again, the location of the maximum cross correlation is the source location. If several relatively similar maximums

exist then multiple hydrophone data may be employed to discern the true source location⁹. This variation of the method will work for very short duration transients, on the order of 100 msec or less.

IV. LOCALIZER APPLICATION

A. MONTEREY BAY EXPERIMENT

As the Collins FEPE is a prototype code, verifying its accuracy required a test to compare with a known signal transmitted in a known ocean waveguide. While solving the forward modeling problem, Westreich¹⁶ tested the code in a shallow water acoustic tomography experiment in Monterey Bay. In December, 1988, a specially designed transmitter produced phase-encoded acoustic signals continuously for four days in the waters off Monterey, California to investigate the feasibility of using tomography for ocean interior and surface monitoring in a coastal environment.¹⁷ This environment presented problems since other methods of predicting the resulting signal at the end of the waveguide would breakdown due to the complexity. The FEPE code accurately modeled the time domain structure of the signal at the receiver when compared to the measured arrivals (Figures 4 and 5). Therefore, in comparison with the measured signal data, the FEPE modeled signal data agreement gave a high degree of confidence in the FEPE algorithm.

The first series of computer experiments for this thesis investigated target localization using the Clay algorithm with the ocean environment of the Monterey Bay. The Collins FEPE code used the same range-independent sound speed profile and range dependent bathymetry as the Monterey Bay tomography experiment (Figures 6 and 7). The modified FEPE code modeled the reciprocal transmission of a Blackman pulse source from the Station J receiver location to predict time domain pressure signals at multiple depths and ranges.¹⁶ The localizer correlated these time domain pressure signals with the

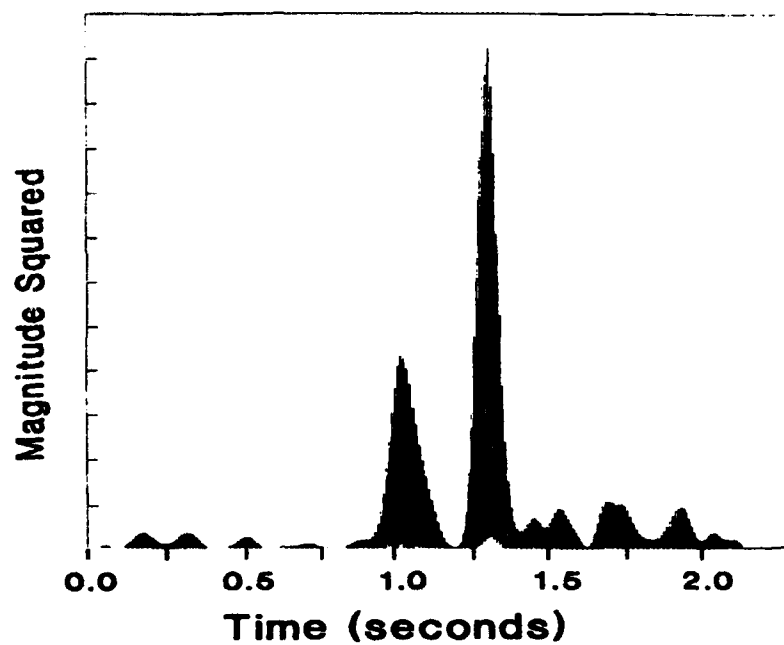


Figure 4: Modeled received signal for Monterey Bay experiment.¹⁶

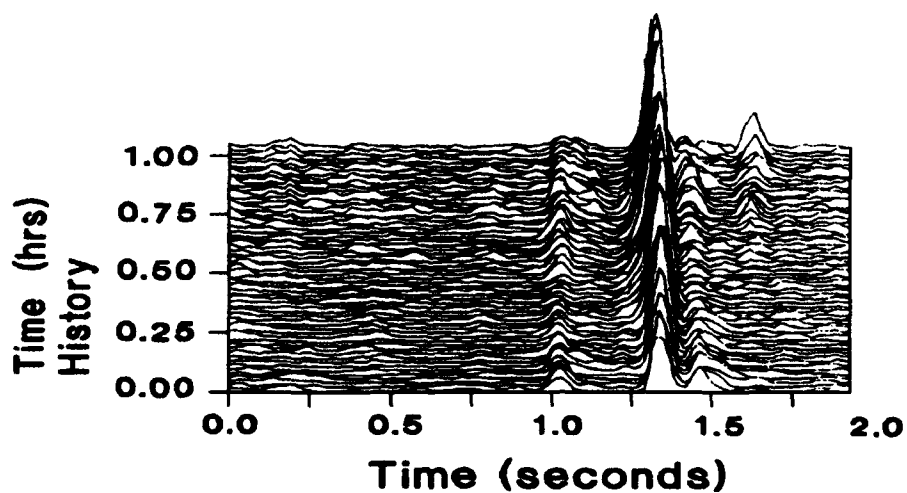


Figure 5: Actual measured signal at Station J in the Monterey Bay experiment.¹⁷

previously modeled received signal for ranges of 30 to 55.75 km from the receiver on a line of bearing to the true source location. The correlator conducted checks on a grid of 1000 meter range increments by 15 meter depth increments. If the grid was appropriately chosen and assuming acoustic reciprocity holds, the algorithm should reveal the true source location at the position of the maximum value of the correlation. Figure 8 and Figure 9 show the maximum values of the normalized correlation coefficient plotted vs. range and depth. The correlation coefficient has its maximum value of 0.92 at the true source depth and range of 55.75 km and 885 m depth. The next highest correlation is 0.76. The maximum value of this model-model correlation was not 1.0 because FEPE is only approximately reciprocal. The degree of reciprocity of FEPE and its sensitivity to different environmental scenarios is an important topic for future research. The complex environment of Monterey Bay reveals a unique target location for a known source.

The localizer results shown in Figure 8 and 9 also show a pronounced maximum. This leads to a problem with the localizer since it is very resolution dependent. As seen in Figure 9, locations within one grid spacing in depth have 0.92 to 0.74 drop in correlation. Therefore the localizer is very dependent on the grid and how it is overlaid upon the environment. Rovero¹⁸ has explored methods that do not suffer as significantly from this criteria.

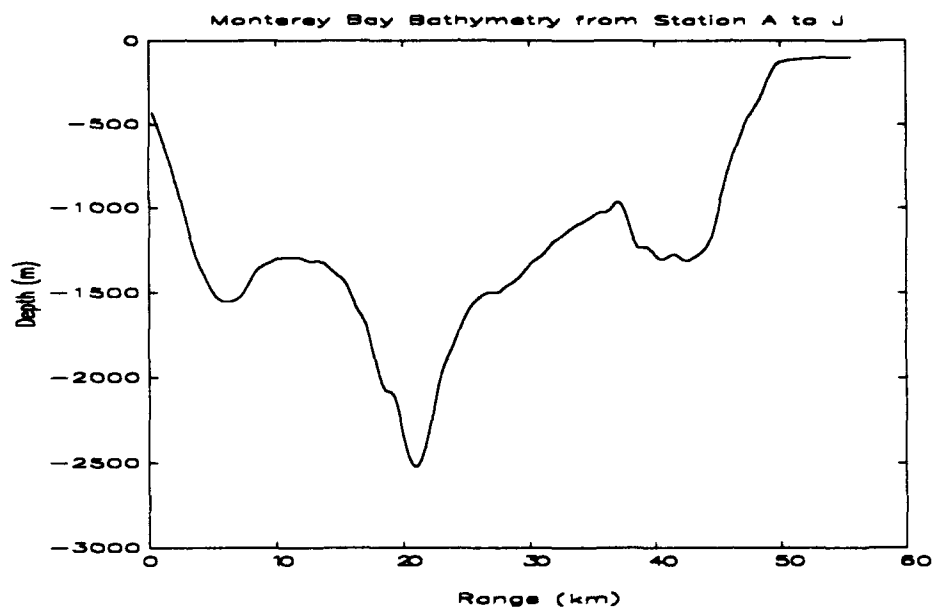


Figure 6: Monterey Bay bathymetry used in FEPE model.

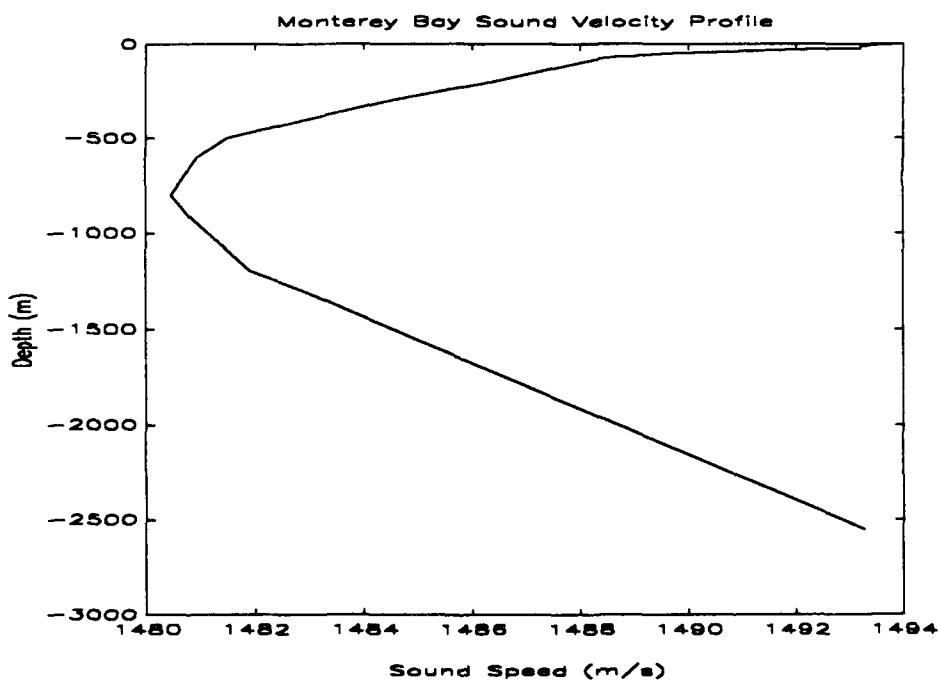


Figure 7: Monterey Bay Sound Velocity Profile used in FEPE model.

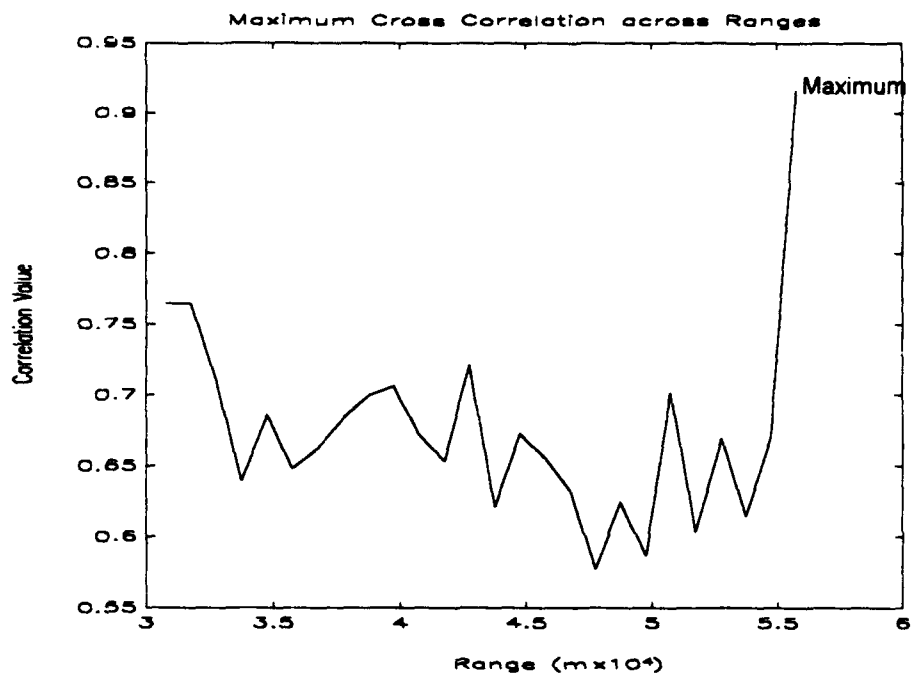


Figure 8: Source localization in range.

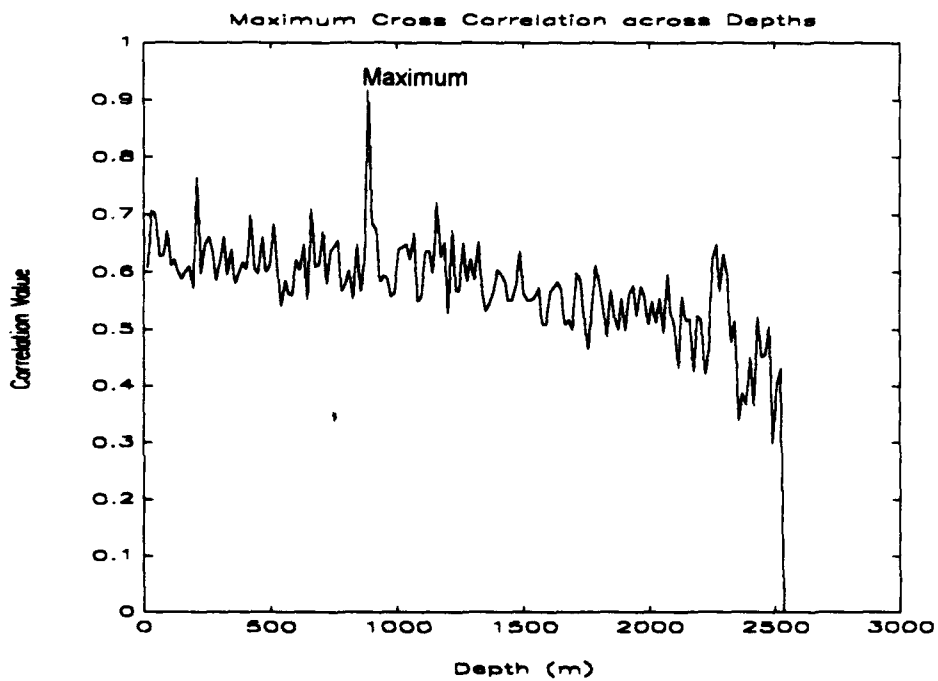


Figure 9: Source localization in depth.

B. BARENTS SEA EXPERIMENT

Here, it is shown that the Clay localization algorithm is relatively insensitive to *a priori* knowledge of the actual signal. An experiment was conducted using the bathymetry and ocean conditions of a tomography experiment scheduled for the summer of 1992 in the Barents Sea. Figure 10 shows the range-independent sound speed profile used as input to FEPE and Figure 11 indicates the bathymetry used as input. The bathymetrically simple region has depth changes from 163 meters to 320 meters, a 0.2 degree slope, over a 56 km range. The algorithm using a modeled signal found the unique source location with a correlation value of 0.88. The next largest coefficient value was 0.76 (Figures 12 and 13).

As in the Monterey Bay experiment, Figures 12 and 13 reveal that the correct location is found, in part, because the grid was placed properly and one of the locations checked was on the grid. This may restrict the algorithm's utility unless a more robust method that resists this dependence is developed. Assuming this condition is met, another criteria that required investigation is that of source signal knowledge.

To determine signal sensitivity the same environmental model was used but a Blackman pulse centered at 500 Hz \pm 50 Hz was used for the source estimate \hat{S} in (15) as shown in

$$R_{om}(\mathbf{r}, z; \tau) = \frac{\text{ifft}(D \cdot (\hat{S}\bar{H})^*(\mathbf{r}, z))}{\sigma_D \sigma_{\bar{H}}} \quad (17)$$

instead of the actual signal. The only commonality between the "true" and "modeled" signal is the bandwidth of the signals (Figure 14).

This approximation of the source lowered the maximum value of the correlation coefficient to 0.54 at the correct location. However, the next largest value of the correlation coefficient was 0.43. As shown in Figures 15 and 16, this initial modification

of the Clay algorithm clearly defined the source location without ambiguity. This shows that very limited information may suffice when attempting to localize a source in shallow water environments.

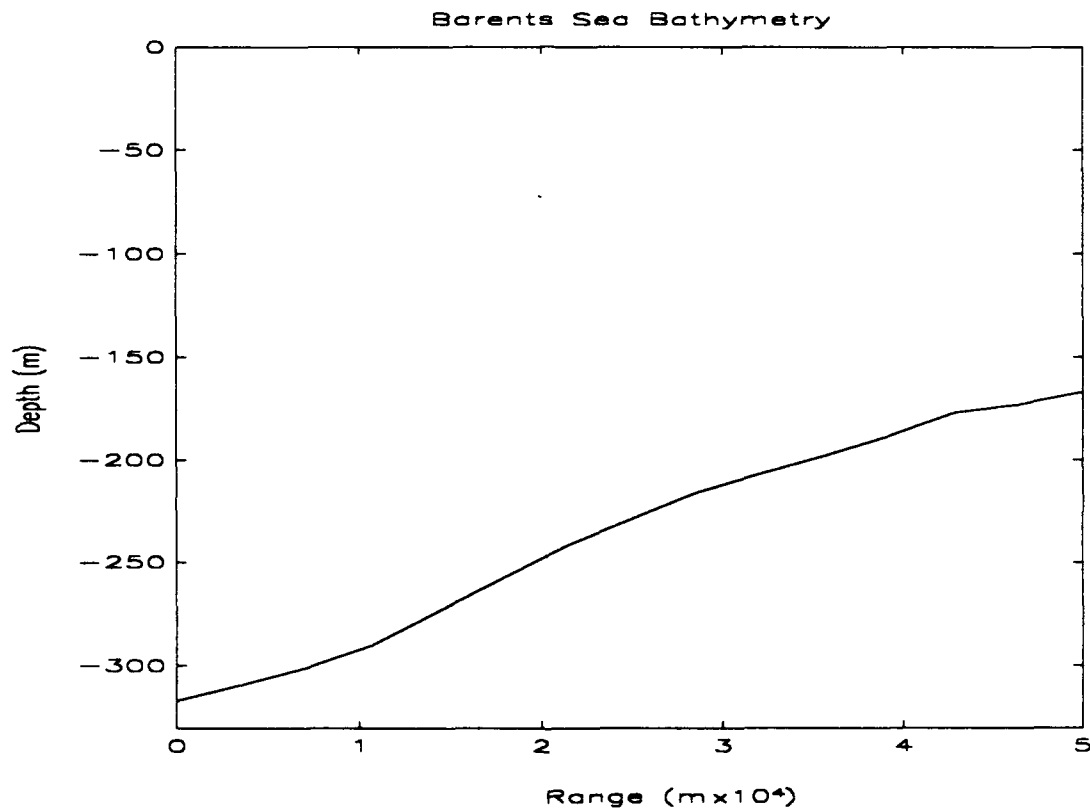


Figure 10: Bathymetry used for Barents Sea FEPE model.

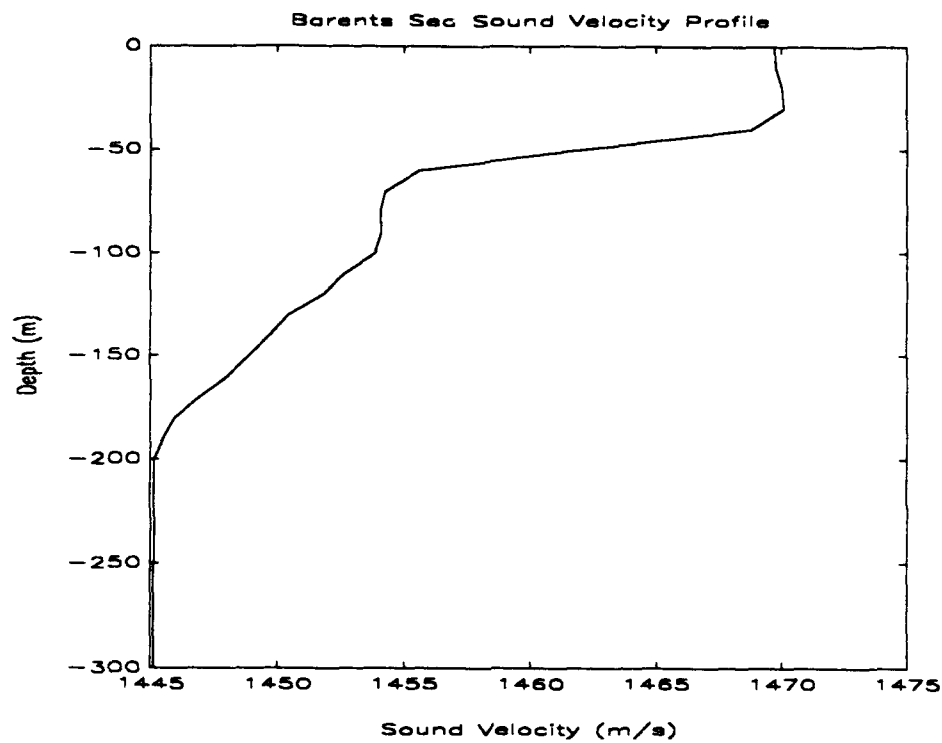


Figure 11: Sound velocity profile used for Barents Sea FEPE model.

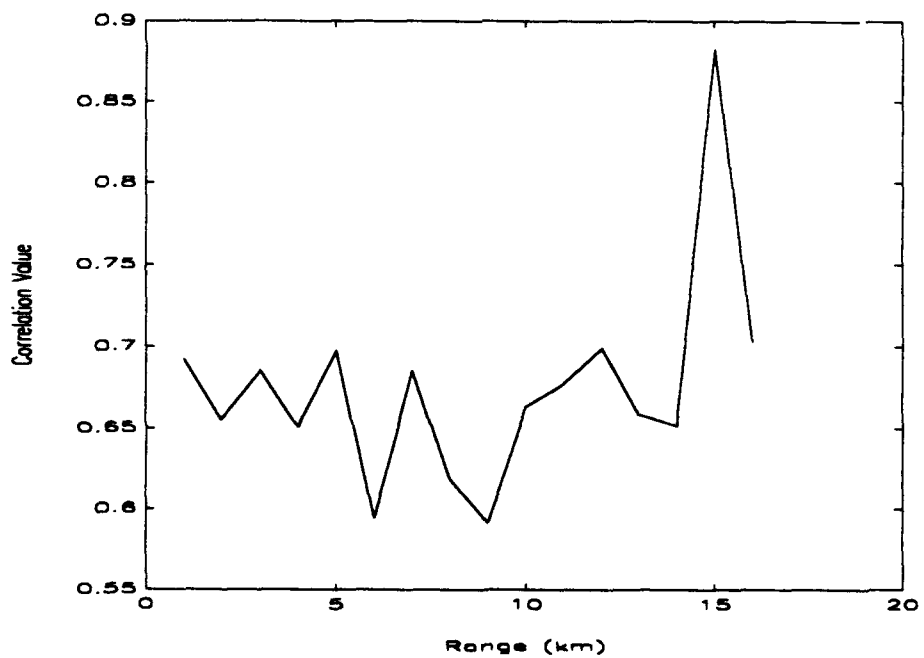


Figure 12: Localization in range for a known signal used when correlating. Source at 15,000 meters range shown.

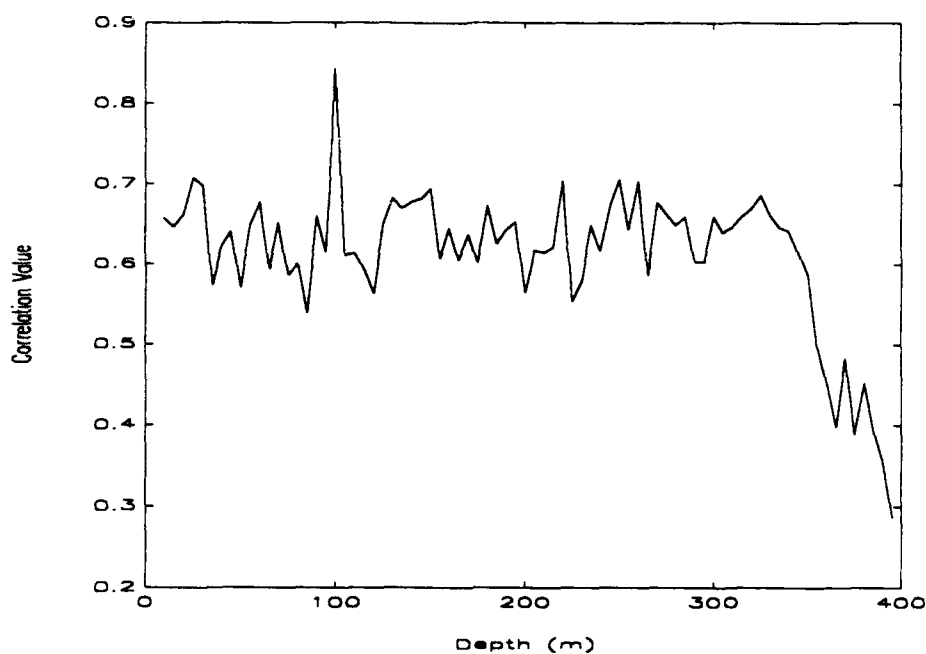


Figure 13: Localization in depth with a known signal used for correlation.

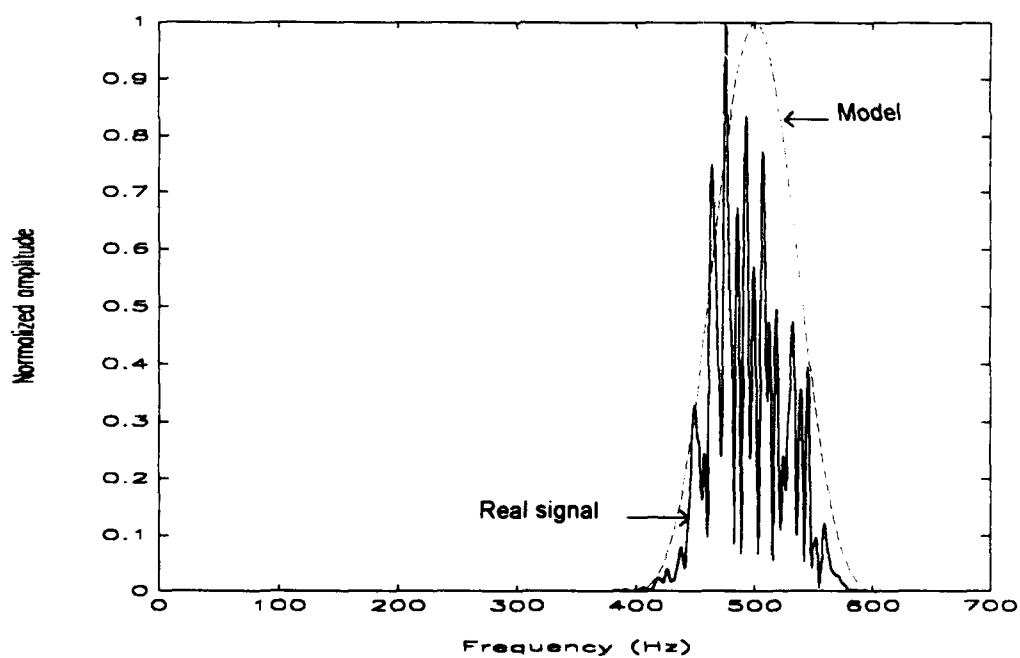


Figure 14: Comparison between "real" signal spectral components and Blackman window model of signal used in Barents Sea computer experiment.

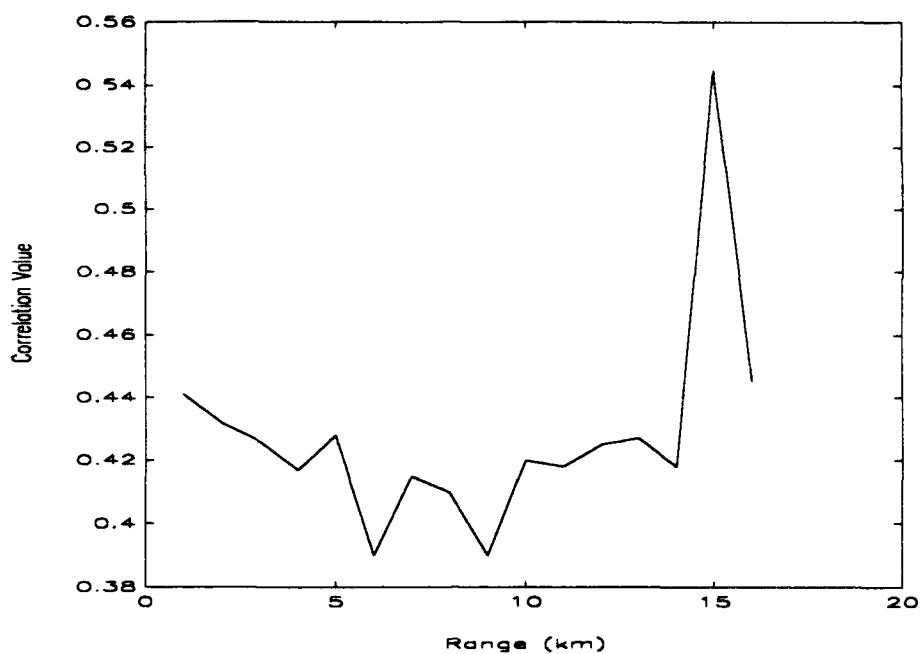


Figure 15: Localization in range with a source assumed as Blackman pulse in the frequency domain between 450 and 550 Hz. Source at 15,000 meters range shown.

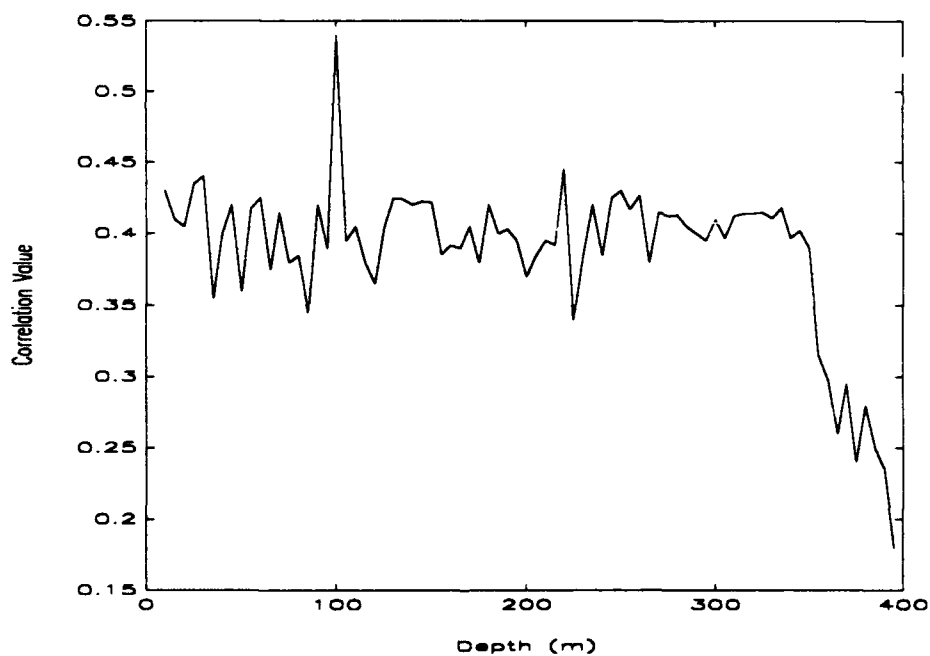


Figure 16: Localization in depth for a source assumed to be Blackman pulse in frequency domain between 450 and 550 Hz. Source depth 100 meters depth shown.

C. GENERIC EXPERIMENT

With the knowledge that for short duration time domain signals, the source signal could be modeled as an impulse in time, a test case was generated to determine a lower bound on the necessity of source signal knowledge. The frequency band occupied by a signal transmitted through the linear time-invariant ocean waveguide will not change.¹⁰ Therefore, a signal that has band limited characteristics could be correlated only over that band. In addition, the signal could be modeled as a constant amplitude over those frequencies. In these experiments, both a Clay localizer and a unknown source localizer are demonstrated for comparison.

1. Flat Waveguide

The source is modeled as a Blackman pulse 224 Hz +/- 16 Hz in a 375 meters deep, 10,000 meters long flat waveguide and with the sound velocity profile shown in Figure 17. The source was located at 150 meters and the receiver at 100 meters. The Clay localizer successfully located the source as expected, with a peak of 1.0 for the correlator value at 150 meters and 10,000 meters (Figures 18 and 19). The reciprocity of FEPE as demonstrated by the near perfect correlation is due to the range independence of the waveguide. The correlation with the impulse response of the ocean waveguide resulted in another accurate localization with suppressed peak of 0.692 (Figures 20 and 21), which was still well above the side-lobe peaks.

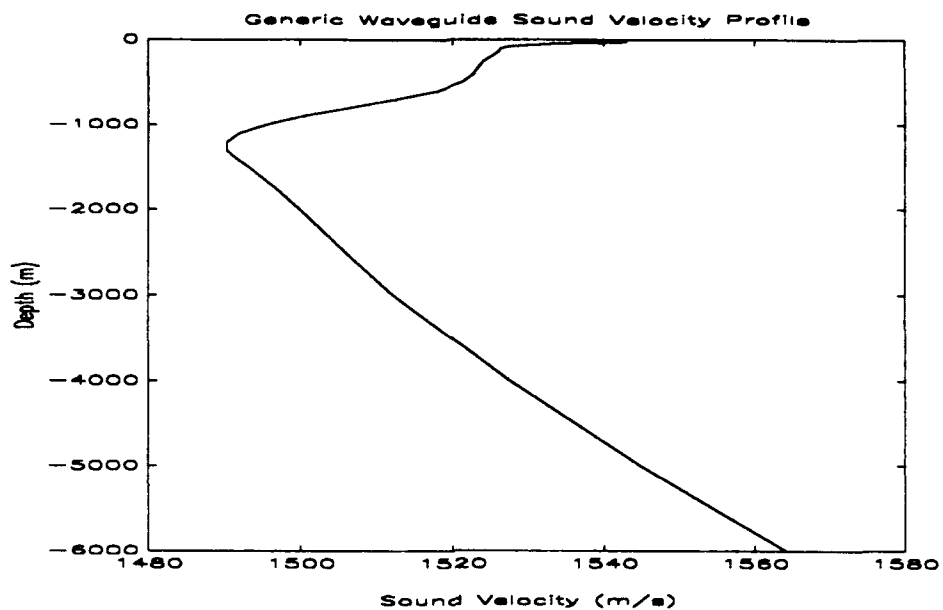


Figure 17: Sound velocity profile used for generic waveguide FEPE model.

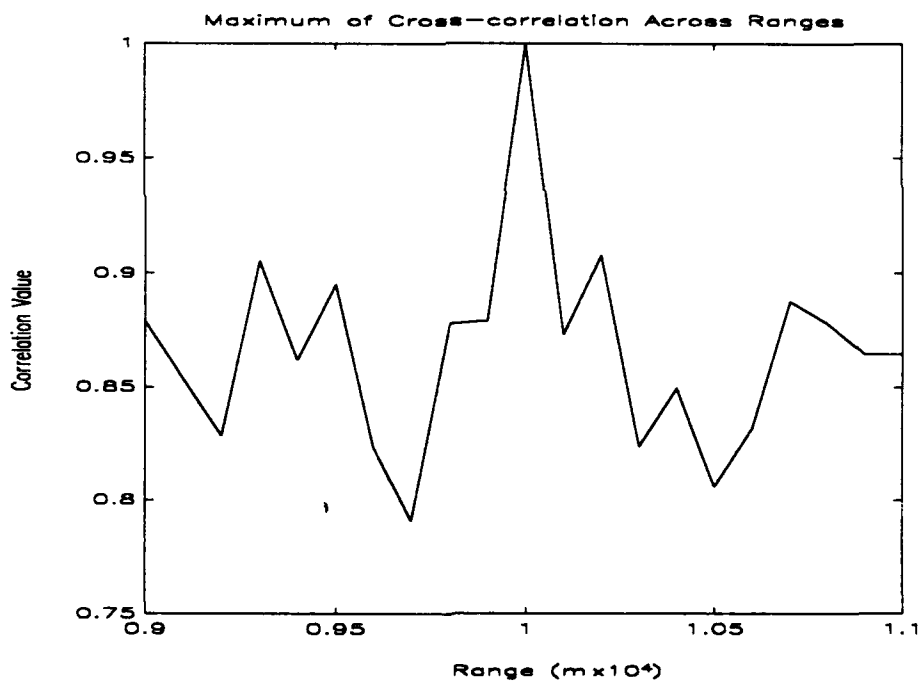


Figure 18: Localization in range for a known signal. Source at a range of 10,000 meters.

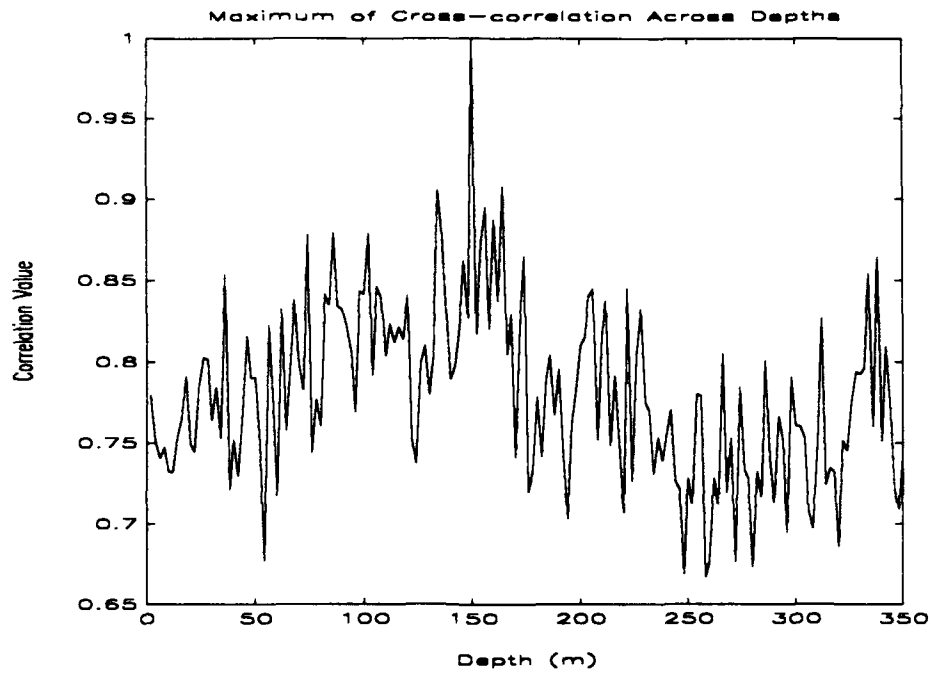


Figure 19: Localization in depth for a known signal. Source at a depth of 150 meters.

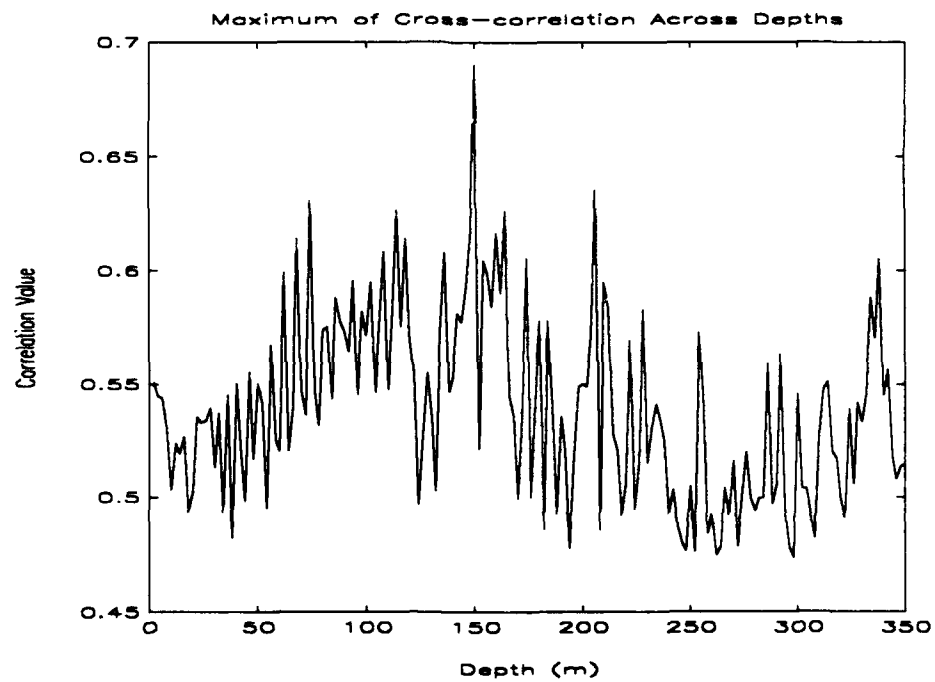


Figure 20: Localization versus depth for an unknown signal (Source signal assumed as impulse in time). Source depth again shown to be 150 meters.

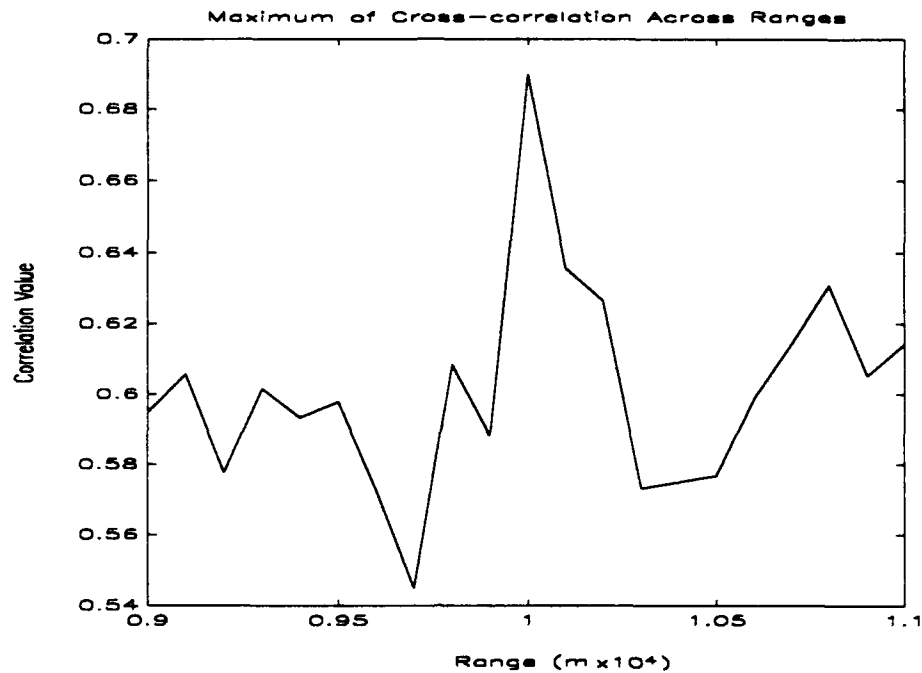


Figure 21: Localization in range for an unknown signal (Source signal assumed to be impulse in time.) Source shown to be from 10,000 meters range.

2. Sloped Waveguide

Figures 22 and 23 show the results of the localizer with no *a priori* source information but in a modified environment from above. In this case FEPE used the same sound velocity profile and a sloping bottom bathymetry, one meter rise for every 500 meters in range, as input. Here the algorithm clearly defines the source location at 10,000 meters range and 150 meters depth. The sharpness of the peak relative to surrounding depths and ranges makes apparent the requirement that the grid must map onto the source location for this algorithm to be successful.

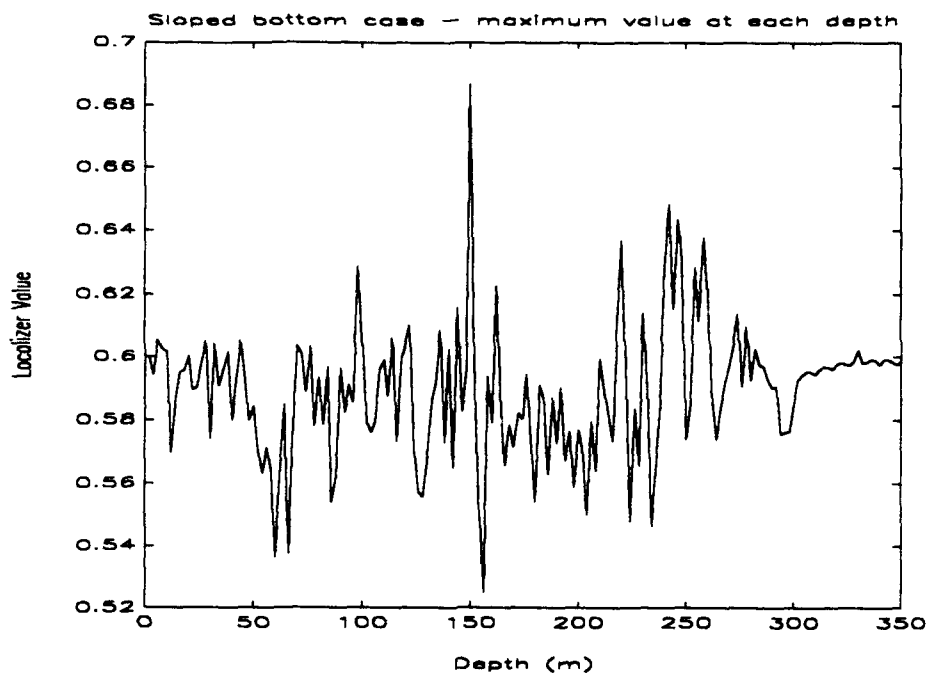


Figure 22: Sloped bottom case, maximum correlation for each depth strata with source depth resolution shown.

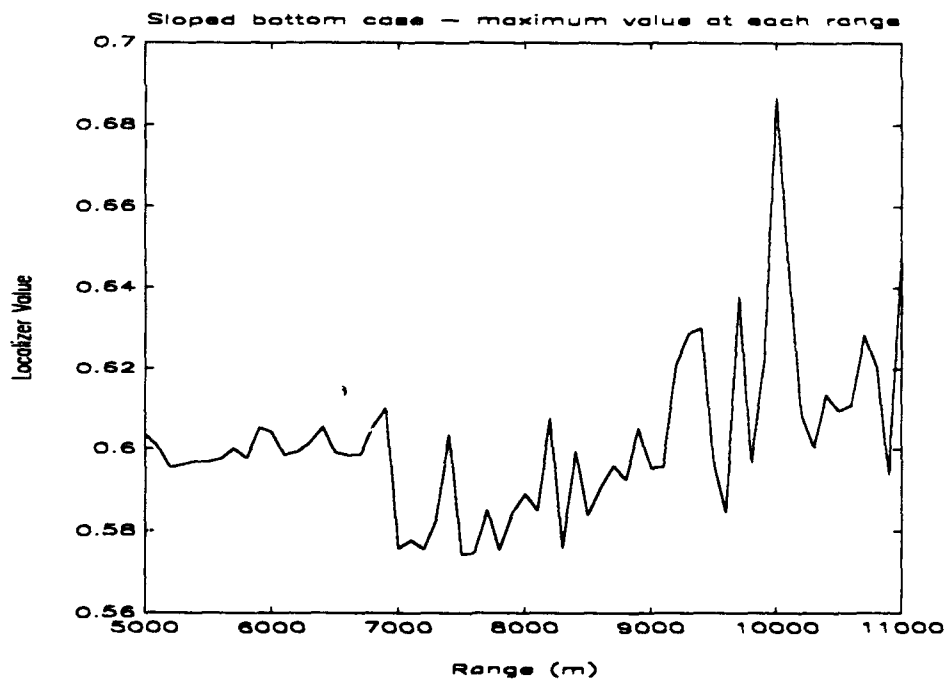


Figure 23: Sloped bottom case, maximum correlation values for each range increment. Source location resolved at 10,000 meters range.

3. Rugged Waveguide

The final case examined used a more rugged bottom profile as shown in Figure 24. This case also resulted in accurate source localization without knowledge of the specific source spectrum. Figures 25 and 26 show the source location clearly defined at 150 meters depth and 10,000 meters range. These do show, however, unexpectedly high values for the localizer for points other than the original source location. Since this environment is more complex than in the prior cases, expectation was that the relative transfer functions would resolve the actual location clearly.

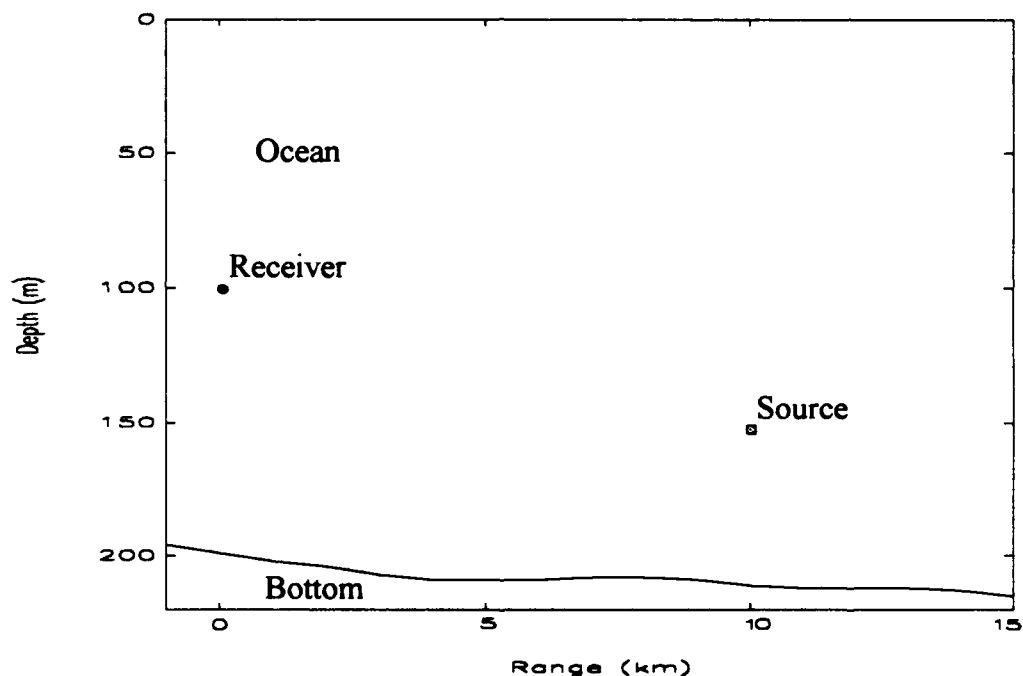


Figure 24: Rugged bathymetry case used in FEPE model input for Generic waveguide tests.

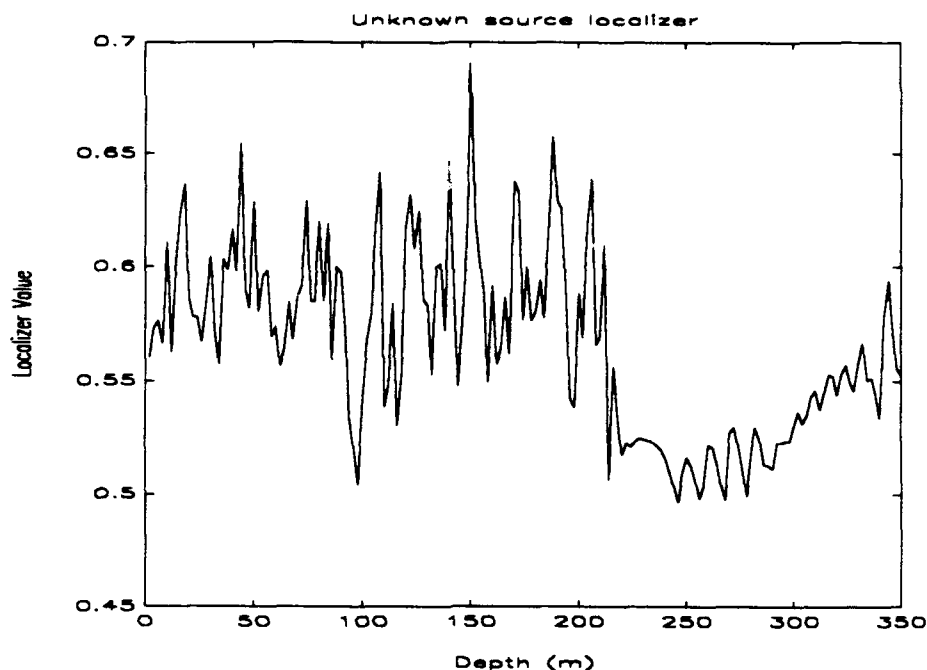


Figure 25: Source localization for rugged bathymetry with no source knowledge maximum values at each depth strata. Source revealed at 150 meters depth.

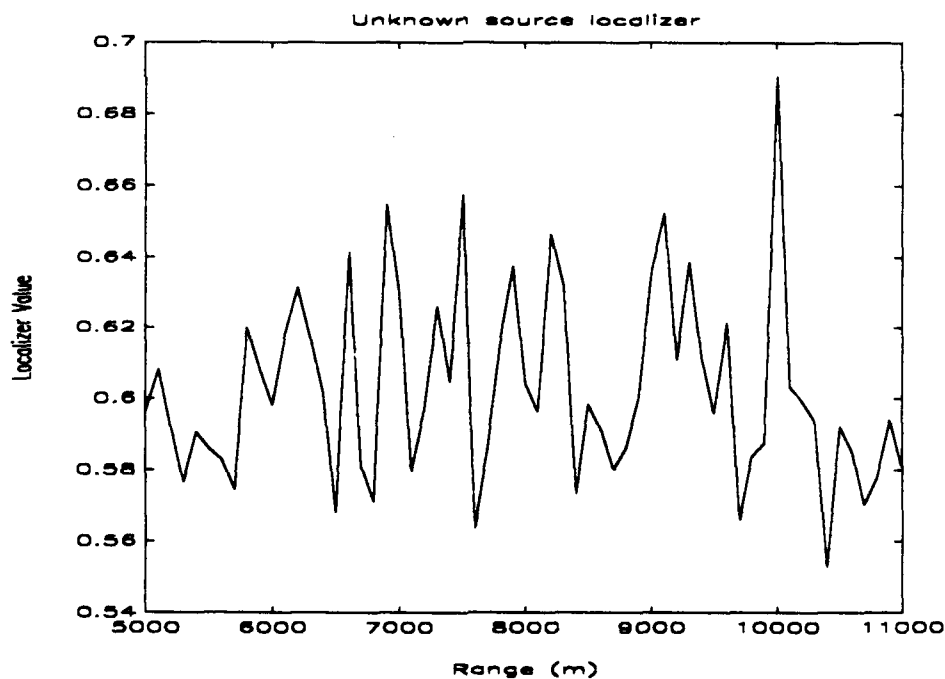


Figure 26: Source localization for rugged bathymetry with no source knowledge maximum values at each range step. Source appears to be at 10,000 meters.

V. CONCLUSIONS

This thesis has shown by computer simulation that transient signals in shallow water environments can be effectively localized. Scenarios used included Monterey Bay, Barents Sea, and generic waveguide simulations in which the signal source was both known and unknown.

Although these were not entirely new methods, this thesis has demonstrated that the short duration time-domain transient localizers work with the Finite Element Parabolic Equation model of Collins. With a well known environment, the algorithms shown have clearly and consistently revealed the transient source location for a variety of cases without ambiguity. Moreover, these investigations demonstrated that source signal parameters need not be completely specified for successful localization. Critical to these developments were the especially important new results that came from the use of the FEPE model to develop the ocean transfer function in the shallow water environments studied.

Future research should include determination of optimum FEPE grid requirements to accurately model transmitted signals when compared to experimentally measured signals. Also to achieve tactical Navy utility¹⁹, the ocean modeling routines and localization algorithms require additional investigations into the effects of environmental uncertainty²⁰ and multiple hydrophone data sets. Computational demands should be explored to determine the best computer architectures for executing these algorithms. Finally, additional topics for future research should include investigation of source localization in noisy environments, integration with detection and classification algorithms, and an investigation of the performance bounds of the FEPE reciprocity.

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